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13. ABSTRACT *(Maximum 200 words)*

The objective of this research project to develop nonlinear multibody computer methodologies that take into account the effect of the three dimensional interaction between the track chains and other vehicle components such as the sprockets, idlers, and the rollers as well as the effect of the dynamic coupling between the rigid body displacements and the elastic deformation of the vehicle components. In the methods developed in this research project, the kinematic degrees of freedom of the track chains are taken into consideration when the dynamic equations of the vehicle are formulated. It is demonstrated that significant reduction in the number of degrees of freedom of the track chains can lead to an inaccurate modeling of the vehicle dynamics and also to numerical difficulties in the computer simulation of this type of vehicles. Therefore, in this research project detailed three dimensional tracked vehicle models that take into account the effect of the chain degrees of freedom are developed.

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1. PROBLEM STATEMENT

The objective of this research project is to develop computational methods for the dynamic, vibration and stress analysis of planar and spatial multibody tracked vehicles that consist of interconnected rigid and deformable bodies. These vehicles which represent many military vehicles and construction machines are traditionally designed using simplified dynamic models or based on static force analysis. As a consequence, there are no in existence today, accurate procedures for the nonlinear dynamic analysis and efficient computer simulation of large scale multi-body tracked vehicles. It is, therefore, the objective of this research project to develop nonlinear multibody computer methodologies that take into account the effect of the three dimensional interaction between the track chains and other vehicle components such as the sprockets, idlers, and the rollers as well as the effect of the dynamic coupling between the rigid body displacements and the elastic deformation of the vehicle components [6]. In the methods developed in this research project, the kinematic degrees of freedom of the track chains are taken into consideration when the dynamic equations of the vehicle are formulated [4,5,13]. It is demonstrated that significant reduction in the number of degrees of freedom of the track chains can lead to an inaccurate modeling of the vehicle dynamics and also to numerical difficulties in the computer simulation of this type of vehicles [3]. Therefore, in this research project detailed three dimensional tracked vehicle models that take into account the effect of the chain degrees of freedom are developed. Specifically, the objectives of this research project can be summarized as follows:

1. Develop accurate three dimensional nonlinear contact force models that describe the interaction between the track links and vehicle components such as the sprockets, idlers, and rollers, as well as the interaction between these links and the ground. These forces which depend on the system generalized coordinates and velocities are used to obtain accurate representation of the complex interaction between the components of the tracked vehicles.

2. Formulate the equations of motion of the spatial tracked vehicles using several approaches. Among these approaches are the *augmented formulation*, the *velocity transformation techniques*, and *recursive methods*. In the augmented formulation, the equations of motion of the vehicle are developed in terms of redundant set of coordinates and the generalized constraint forces which are expressed in terms of Lagrange multipliers. This formulation leads to a mixed system of differential and algebraic equations. An iterative Newton-Raphson algorithm can be used to check on the violation of the kinematic constraints. In the velocity transformation and the recursive methods, the use of the iterative Newton-Raphson method can be avoided by expressing the system coordinates in terms of the independent joint variables.

3. Develop recursive methods that exploit the peculiar characteristics of tracked vehicles. In these algorithms, the tracked vehicle is assumed to consist of kinematically decoupled subsystems. The first subsystem consists of the chassis, the sprockets, the idlers, and the rollers. The other subsystems consist of the two

kinematically decoupled track chains.

4. Develop a three dimensional finite element procedure for the deformation and stress analysis of the track links. In this procedure, the inertia, joint, and contact forces are accurately calculated and used to determine the deformation and stresses in the track links as the result of their interaction with the ground and vehicle components.

The objectives of this research project have not been modified from the original application.

2. MAIN RESULTS

Since the start of this project in May of 1994, the folowing tasks have been completed:

1. The validity of using the method of the static force analysis which is traditionally used in the design of tracked vehicles was examined and it was demonstrated that the use of such a method can lead to significant errors in the stresses when the deformation of the track links are considered [7]. A planar tracked vehicle model that consists of fifty four bodies was used as the study model, and the track is modeled as a closed loop kinematic chain that consists of forty two links connected by forty two revolute joints. The contact forces between the track links and the ground, idler, sprocket, and rollers are represented by continuous force models. The sprocket teeth is represented by three surfaces; the right surface, the left surface, and the seating surface. A coordinate system is attached to each of these surfaces, and a constant transformation matrix is used to define the orientation of each of these surfaces with respect to the tooth surface. The nonlinear kinematic conditions that define the interaction between the track links and the vehicle components are developed and used to define the high frequency contact forces that define the dynamic interaction between the links of the track and the vehicle components. Expressions for all the dynamic forces such as the centrifugal and Coriolis forces, contact forces, and inertia forces are developed and the effect of the track link deformations on some of these forces is examined. The results obtained demonstrated that while the contact forces have the most significant effect on the track dynamics, the use of the methods of the static force analysis can lead to significant errors in the stresses obtained for the track links.

2. A procedure for the dynamic analysis of planar flexible multi-body tracked vehicles using experimentally identified modal parameters was developed [6]. The mode shapes, frequencies, and modal mass, damping and stiffness coefficients which are determined using experimental modal analysis are used to introduce the deformation degrees of freedom of the chassis of the vehicle. Since, in flexible multi-body simulations, the chassis component modes must be extracted from the component modes of the assembled vehicle, a two-frequency scale system was identified, and it

was demonstrated that the change in the inertia and stiffness of the fast system does not have a significant effect on the mode shapes and natural frequencies of the slow system. This fact was used to identify the chassis mode shapes from the experimentally identified mode shapes of the assembled vehicles. The results obtained using the experimentally identified parameters and the finite element method were compared.

3. The effect of using the finite element incremental approach on modeling the rigid body inertia was examined, and it was demonstrated that the use of this approach in multibody simulations can lead to significant errors in the dynamic equations [8,9]. For this reason, a set of coordinate systems that leads to exact representation of the rigid body inertia must be used in the nonlinear dynamic analysis of vehicle systems. These coordinate systems include an intermediate element coordinate system which has an origin rigidly attached to the origin of the deformable body coordinate system and has axes which are initially parallel to the axes of the element coordinate system. By using this intermediate element coordinate system, and the fact that the finite element shape functions can describe an arbitrary rigid body translations, a nonlinear formulation that leads to exact modeling of the rigid body dynamics can be developed. Numerical examples are used to demonstrate the errors in the rigid body motion when linearization techniques are used.

4. A spatial formulation for the nonlinear contact forces that represent the interaction between the track links and the ground as well as the vehicle components such as the sprockets, idlers, and rollers was developed [4,5,13]. Spatial coordinate systems were introduced to define the relative translations and rotations between the surfaces which come in contact. These coordinate systems were used to develop the nonlinear kinematic equations that define the contact conditions. In order to describe the engagement between the sprockets and the track link pins, each sprocket teeth is described using three surfaces. These are the *right surface*, the *seating surface*, and the *left surface*. These surfaces are assumed to have a constant orientation with respect to a tooth coordinate system which is also assumed to have a constant orientation with respect to the sprocket coordinate system. The nonlinear driving forces as the result of the interaction between the sprocket teeth and the track links are expressed in terms of the generalized coordinates of the tracked vehicles.

5. A three dimensional vehicle model that includes significant details was developed for the nonlinear dynamic analysis of large scale multibody tracked vehicle systems [4,5,13]. In this model, the joint articulation of the track chains are taken into consideration so as to allow the development of a computational procedure for the analysis of the vibration and contact forces of complex multibody tracked vehicle systems. The three dimensional tracked vehicle system is assumed to consist of three kinematically decoupled subsystems which include the chassis subsystem, and two track subsystems. A recursive approach for formulating the nonlinear equations of the

vehicle based on the velocity transformation was developed in order to reduce the number of equations, avoid the solution of a system of differential and algebraic equations, and avoid the use of nonholonomic constraints to describe the sprocket rotations. The singular configurations of the closed kinematic chains of the track are also avoided by using a penalty function approach to define the constraint forces at selected secondary joints of the track. Detailed three dimensional nonlinear contact force models that describe the interaction between the track links and the vehicle components such as the rollers, sprockets, and idlers as well as the interaction between the track links and the ground were developed and used to define the generalized contact forces associated with the degrees of freedom of the vehicle. The effect of the tangential and friction forces on the stability of the vehicles was also examined. A computer simulation of a tracked vehicle that consists of one hundred and six bodies and has one hundred and eighteen degrees of freedom was used in order to demonstrate the use of the formulations developed in this project.

6. In flexible body dynamics, the body coordinate system and the component modes can not be arbitrarily or independently selected. The shape functions are defined in a coordinate system, and therefore, the expressions of these functions define the nature of the deformable body coordinate system. It was demonstrated in this research project that the resonance conditions are not absolute in the sense that different resonance frequencies can be obtained for the same system if the deformation is defined in different coordinate systems that can have arbitrary rigid body displacements [10]. As a consequence, speaking of the resonance phenomenon must be associated with the selection of the coordinate system of the deformable body. Only geometric conditions are required to define the coordinate system of the elastic body, and as such, natural force conditions are of much less significance in defining the resonance conditions. The analytical results obtained in this research project clearly explain why two different sets of mode shapes and two different sets of coordinate systems can be used to obtain approximately the same displacement solutions in multibody simulations. The fundamental relationship between the selection of the component modes and the deformable body coordinate system is investigated and it is demonstrated that a proper selection of the deformable body coordinate system does not only lead to a consistent formulation, but it also leads to a proper definition of the resonance conditions.

7. The linearization resulting from the use of the finite element incremental approach in the analysis of *spatial flexible multibody systems* is investigated [12]. Finite element shape functions that describe arbitrary rigid body translations can be used to obtain a non-linear flexible multibody formulation that leads to exact modeling of the spatial rigid body inertia when the structures rotate as rigid bodies. Introducing an intermediate element coordinate system, which has an origin rigidly attached to the origin of the deformable body coordinate system and has axes which are parallel to the axes of the element coordinate system in the undeformed configuration, leads to

exact modeling of the rigid body dynamic equations (as pointed out in Task 3 for the case of planar motion). The large rigid body translational and rotational displacements can be described using a set of reference coordinates that define the location of the origin and the orientation of the deformable body coordinate system. Existing finite element incremental formulations, on the other hand, do not lead to exact modeling of the rigid body inertia of beams and plates when used in flexible multibody simulations [12]. As demonstrated in this research project, the incremental finite element formulations do not lead to the exact spatial rigid body mass moments and products of inertia when the structures move as rigid bodies. As a consequence, such formulations do not lead to the correct rigid body equations of motion.

8. A comparative numerical study was performed to evaluate the performance of different numerical schemes and formulations used in the computer aided analysis of large scale three dimensional multibody tracked vehicles. The numerical results obtained in this study demonstrate that the technique of the velocity transformation is more stable and robust when it is used in the computer aided analysis of spatial tracked vehicles. When other techniques such as the fully recursive method and the augmented formulation that employs Lagrange multipliers are used, numerical difficulties were encountered and the simulation becomes very inefficient. In the recursive methods, the nonlinear dynamic equations of the spatial tracked vehicle are expressed in terms of a minimum set of independent coordinates, thereby eliminating all the algebraic constraint equations. This formulation, however, leads to a highly nonlinear dense inertia matrix. In the augmented formulation, the nonlinear dynamic equations of the three dimensional vehicle are formulated in terms of a redundant set of coordinates, and as a consequence, a set of algebraic and differential equations must be solved simultaneously. The algorithm based on the augmented formulation requires the use of an iterative Newton-Raphson algorithm, and in tracked vehicle applications, such an algorithm is prone to numerical instability.

9. Optimized computer and numerical algorithms for the dynamic analysis of spatial tracked vehicle systems were also developed. Detailed three dimensional models that describe the interaction between the vehicle components were developed using a spatial multibody tracked vehicle that consists of one hundred and six bodies. Each of the track chains consists of forty two links connected by revolute joints. Because of the high frequency impulsive contact forces, the simulation of these vehicles requires extensive computations. The initial simulation results of the tracked vehicle model used in this investigation indicate that one second of real time simulation takes approximately twenty nine minutes of CPU time on a main frame IBM 3090. During the last year, optimized numerical codes were developed and a reduction of approximately 50% of the simulation time could be achieved. The robustness of the numerical algorithms developed in this investigation was tested using different simulation configurations which include straight line motion of the vehicle, motion of the vehicle over bumps, and turning motion.

10. A finite element procedure for the stress analysis of the track links using the three dimensional dynamic contact forces obtained from the multibody simulations was developed [1,2]. A computer program was developed to obtain the three dimensional inertia shape integrals that appear in the flexible multibody equations of the track link. This computer program is used to automatically develop the vibration equations of the links of the track chains subject to the impulsive contact, joint, and inertia forces. The effect of the impulsive contact, inertia, and joint forces on the dynamic stresses was examined. In the stress analysis procedure developed in this study, the dynamic mode shapes of each link of the track chains are determined using a detailed finite element model. The natural frequencies and mode shapes determined using the finite element method are verified using experimental identification techniques.

3. LIST OF PUBLICATIONS

The formulations and procedures developed, and the results obtained in this research project are documented in the following publications:

1. " Chain Link Deformation in the Nonlinear Dynamics of Tracked Vehicles", *Journal of Vibration and Control*, Vol. 1, No. 2, 1995, pp. 201-224.

2. " Dynamics of Multibody Tracked Vehicles Using Experimentally Identified Modal Parameters", *ASME Journal of Dynamic Systems, Measurement, and Control*, Vol. 118(3), 1996, pp. 449-507.

3. " Finite Element Incremental Approach and Exact Rigid Body Inertia", *ASME Journal of Mechanical Design*, Vol. 118(2), 1996, pp. 171-178.

4. " Resonance Conditions and Deformable Body Coordinate Systems" *Journal of Sound and Vibration*, Vol. 192, No. 1, 1996, pp. 389-398.

5. " Nonlinear Dynamics and Vibrations of Three Dimensional Tracked Vehicles", Proceedings of the 24th Biennial Mechanisms Conference, ASME 1996 Design Engineering Technical Conferences, August 18-22, 1996, Irvine, California.

6. " Approximation Methods in the Nonlinear Analysis of Multibody Tracked Vehicles", *Journal of Vehicle System Dynamics*, accepted for publication.

7. "Definition of the Slopes and the Finite Element Absolute Nodal Coordinate Formulation", *Journal of Multibody System Dynamics*, Vol. 1, No.3, 1997, pp. 339-348 .

8. " Three Dimensional Absolute Nodal Coordinate Formulation: Plate Problem",

International Journal for Numerical Methods in Engineering, Vol. 40, No. 15, August 1997, pp. 2775-2790.

9. " Exact Modeling of the Rigid Body Inertia Using the Finite Element Method", *ASME Journal of Vibration and Acoustics*, accepted for publication.

10. " Spatial Dynamics of Multibody Tracked Vehicles: Spatial Equations of Motion", *Journal of Vehicle System Dynamics*, accepted for publication.

11. " Spatial Dynamics of Multibody Tracked Vehicles: Contact Forces and Simulation Results", *Journal of Vehicle System Dynamics*, accepted for publication.

12. "Chain Vibration and Dynamic Stress in Three-Dimensional Tracked Vehicles: Dynamic Model", Submitted to *Journal of Multibody System Dynamics*.

13. "Chain Vibration and Dynamic Stress in Three-Dimensional Tracked Vehicles: Deformation and Stress Results", Submitted to *Journal of Multibody System Dynamics*.

4. SCIENTIFIC PERSONNEL

The list of all researchers who participated and supported by this research project is as follows:

1. Jin-Hwan Choi, graduate research assistant.
2. Andrew Christensen, graduate research assistant.
3. Haichiang Lee, graduate research assistant.
4. Marcello Campanile, graduate research assistant.
5. Hussien A. Hussien, graduate research assistant
5. Ahmed A. Shabana, principal investigator.

The degrees awarded are as follows:

1. Ph.D. degree to Dr. J.H. Choi, 1996
2. Ph.D. degree to Dr. H.C. Lee, 1996
3. M.S. degree to Mr. A. Christensen, 1994
4. Ph.D. degree to Mr. M. Campanelli, expected May 1998
5. Ph.D. degree to Mr. H. Hussien, expected May 1998

5. REFERENCES

1. Campanelli, M., Choi, J.H., Lee, H.C., and Shabana, A.A., "Chain Vibration and Dynamic Stress in Three-Dimensional Tracked Vehicles: Dynamic Model", Submitted to *Journal of Multibody System Dynamics*.

2. Campanelli, M., Choi, H.C., and Shabana, A.A., "Chain Vibration and Dynamic Stress in Three-Dimensional Tracked Vehicles: Deformation and Stress Results", Submitted to *Journal of Multibody System Dynamics*.

3. Choi, J.H., Campanelli, M., Shabana, A., and Wehage, R.A., " Approximation Methods in the Nonlinear Analysis of Multibody Tracked Vehicles", Journal of *Vehicle System Dynamics*.

4. Choi, J.H., Lee, H.C., and Shabana, A.A.," Spatial Dynamics of Multibody Tracked Vehicles: Spatial Equations of Motion", Submitted to the Journal of *Vehicle System Dynamics*.

5. Lee, H.C., Choi, J.H., and Shabana, A.A.," Spatial Dynamics of Multibody Tracked Vehicles: Contact Forces and Simulation Results", Submitted to the Journal of *Vehicle System Dynamics*.

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8. Shabana, A.A., " An Absolute Nodal Coordinate Formulation for the Large Rotation and Deformation Analysis of Flexible Bodies", Technical Report # MBS96-1-UIC, Department of Mechanical Engineering, University of Illinois at Chicago.

9. Shabana, A.A., " Finite Element Incremental Approach and Exact Rigid Body Inertia", *ASME Journal of Mechanical Design*, Vol. 118(2), 1996, pp. 171-178.

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Definition of the Slopes", Journal of *Multibody System Dynamics*, accepted for publication.

12. Shabana, A.A., and Christensen, A., " Three Dimensional Absolute Nodal Coordinate Formulation: Plate Problem", *International Journal for Numerical Methods in Engineering*, Vol. 40, No. 15, August 1997, pp. 2775-2790.

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